Nuclear power plant

A nuclear power station (Grafenrheinfeld Nuclear Power Plant, Grafenrheinfeld, Bavaria, Germany). The nuclear reactor is contained inside the spherical containment building in the center – left and right are cooling towers which are common cooling devices used in all thermal power stations, and likewise, emit water vapor from the non-radioactive steam turbine section of the power plant.

Bohunice Nuclear Power Plant in Jaslovské Bohunice in Slovakia.

A **nuclear power plant** or **nuclear power station** is a thermal power station in which the heat source is a nuclear reactor. As it is typical of thermal power stations, heat is used to generate steam that drives a steam turbine connected to a generator that produces electricity. As of 23 April 2014, the IAEA report there are 450 nuclear power reactors in operation[1] operating in 31 countries.[2]

Nuclear plants are usually considered to be base load stations since fuel is a small part of the cost of production[3] and because they cannot be easily or quickly dispatched. Their operations and maintenance (O&M) and fuel costs are, along with hydropower stations, at the low end of the spectrum and make them suitable as base-load power suppliers. The cost of spent fuel management, however, is somewhat uncertain.

History

The control room at an American nuclear power station

Electricity was generated by a nuclear reactor for the first time ever on September 3, 1948 at the X-10 Graphite Reactor in Oak Ridge, Tennessee in the United States, which was the first nuclear power station to power a light bulb.[4][5][6] The second, larger experiment occurred on December 20, 1951 at the EBR-I experimental station near Arco, Idaho in the United States. On June 27, 1954, the world's first nuclear power station to

generate electricity for a power grid started operations at the Soviet city of Obninsk.[7] The world's first full scale power station, Calder Hall in England, opened on October 17, 1956.[8] The world's first full scale power station solely devoted to electricity production (Calder Hall was also meant to produce plutonium), Shippingport power plant in the United States, connected to the grid on December 18, 1957.

Components

The key components common to current nuclear power plants are:

- **Reactor assembly**
  - Nuclear fuel
  - Nuclear reactor core
  - Neutron moderator
  - Startup neutron source
  - Neutron poison
  - Neutron howitzer (provides steady source of neutrons to re-initiate reaction following shutdown)
  - Coolant (often the Neutron Moderator and the Coolant are the same, usually both purified water)
  - Control rods
  - Reactor pressure vessel (RPV)

- **Steam generation**
  - Boiler feedwater pump
  - Steam generators (not in BWRs)
- **Power generation**
  - Steam turbine
  - Electrical generator
  - Condenser
  - Cooling tower (not always required)
- **Fuel handling**
  - Radwaste System (a section of the plant handling radioactive waste)
  - Refueling Floor
  - Spent fuel pool
- **Safety systems**

- Reactor Protective System (RPS)
- Emergency Diesel Generators
- Emergency Core Cooling Systems (ECCS)
- Standby Liquid Control System (emergency boron injection, in BWRs only)
- Essential service water system (ESWS)
- Containment building

▪ **Controls**

- Control room
- Emergency Operations Facility

- Nuclear training facility (usually contains a Control Room simulator)

Systems

BWR schematic

Pressurized water reactor

Primary coolant system showing reactor pressure vessel (red), steam generators (purple), pressurizer (blue), and pumps (green) in the three coolant loop Hualong One pressurized water reactor design

The conversion to electrical energy takes place indirectly, as in conventional thermal power stations. The fission in a nuclear reactor heats the reactor coolant. The coolant may be water or gas or even liquid metal depending on the type of reactor.

The reactor coolant then goes to a steam generator and heats water to produce steam. The pressurized steam is then usually fed to a multi-stage steam turbine. After the steam turbine has expanded and partially condensed the steam, the remaining vapor is condensed in a condenser. The condenser is a heat exchanger which is connected to a secondary side such as a river or a cooling tower. The water is then pumped back into the steam generator and the cycle begins again. The water-steam cycle corresponds to the Rankine cycle.

Nuclear reactor

The nuclear reactor is the heart of the station. In its central part, the reactor's core produces heat due to nuclear fission. With this heat, a coolant is heated as it is pumped through the reactor and thereby removes the energy from the reactor. Heat from nuclear fission is used to raise steam, which runs through turbines, which in turn powers the electrical generators.

Nuclear reactors usually rely on uranium to fuel the chain reaction. Uranium is a very heavy metal that is abundant on Earth and is found in sea water as well as most rocks. Naturally occurring uranium is found in two different isotopes: uranium-

238 (U-238), accounting for 99.3% and uranium-235 (U-235) accounting for about 0.7%. Isotopes are atoms of the same element with a different number of neutrons. Thus, U-238 has 146 neutrons and U-235 has 143 neutrons. Different isotopes have different behaviours. For instance, U-235 is fissile which means that it is easily split and gives off a lot of energy making it ideal for nuclear energy. On the other hand, U-238 does not have that property despite it being the same element. Different isotopes also have different half-lives. A half-life is the amount of time it takes for half of a sample of a radioactive element to decay.

U-238 has a longer half-life than U-235, so it takes longer to decay over time. This also means that U-238 is less radioactive than U-235.

Since nuclear fission creates radioactivity, the reactor core is surrounded by a protective shield. This containment absorbs radiation and prevents radioactive material from being released into the environment. In addition, many reactors are equipped with a dome of concrete to protect the reactor against both internal casualties and external impacts.[9]

Steam turbine

The purpose of the steam turbine is to convert the heat contained in steam into mechanical energy. The engine house with the steam turbine is usually structurally separated from the main reactor building. It is so aligned to prevent debris from the destruction of a turbine in operation from flying towards the reactor.

In the case of a pressurized water reactor, the steam turbine is separated from the nuclear system. To detect a leak in the steam generator and thus the passage of radioactive water at an early stage, an activity meter is mounted to track the outlet steam of the steam generator. In

contrast, boiling water reactors pass radioactive water through the steam turbine, so the turbine is kept as part of the radiologically controlled area of the nuclear power station.

Generator

The generator converts mechanical power supplied by the turbine into electrical power. Low-pole AC synchronous generators of high rated power are used.

Cooling system

A cooling system removes heat from the reactor core and transports it to another area of the station, where the thermal energy can be harnessed to produce electricity or to do other useful work. Typically the hot coolant is used as a heat source for a boiler, and the pressurized steam from that drives one or more steam turbine driven electrical generators.[10]

Safety valves

In the event of an emergency, safety valves can be used to prevent pipes from bursting or the reactor from exploding. The valves are designed so that they can derive all of

the supplied flow rates with little increase in pressure. In the case of the BWR, the steam is directed into the suppression chamber and condenses there. The chambers on a heat exchanger are connected to the intermediate cooling circuit.

Main condenser

The main condenser is a large cross-flow tube-and-shell heat exchanger that takes wet vapor, a mixture of liquid water and steam at saturation conditions, from the turbine-generator exhaust and condenses it back into sub-cooled liquid water so it

can be pumped back to the reactor by the condensate and feedwater pumps.[11] In the main condenser the wet vapor turbine exhaust come into contact with thousands of tubes that have much colder water flowing through them on the other side. The cooling water typically come from a natural body of water such as a river or lake. Palo Verde Nuclear Generating Station, located in the desert about 60 miles west of Phoenix, Arizona, is the only nuclear facility that does not use a natural body of water for cooling, instead it uses treated sewage from the greater Phoenix metropolitan area. The water coming from the cooling body of water is either pumped

back to the water source at a warmer temperature or returns to a cooling tower where it either cools for more uses or evaporates into water vapor that rises out the top of the tower. [12]

Feedwater pump

The water level in the steam generator and the nuclear reactor is controlled using the feedwater system. The feedwater pump has the task of taking the water from the condensate system, increasing the pressure and forcing it into either the steam generators (in the case of a

pressurized water reactor) or directly into the reactor (for boiling water reactors).

Emergency power supply

Most nuclear stations require two distinct sources of offsite power feeding station service transformers that are sufficiently separated in the station's switchyard and can receive power from multiple transmission lines. In addition in some nuclear stations, the turbine generator can power the station's house loads while the station is online via station service transformers which tap power from the generator output bus bars before they

reach the step-up transformer (these stations also have station service transformers that receive offsite power directly from the switch yard). Even with the redundancy of two power sources total loss of offsite power is still possible. Nuclear power stations are equipped with emergency power.

Workers in a nuclear power station

- Nuclear engineers
- Reactor operators
- Health physicists
- Emergency response team personnel

- Nuclear Regulatory Commission Resident Inspectors

In the United States and Canada, workers except for management, professional (such as engineers) and security personnel are likely to be members of either the International Brotherhood of Electrical Workers (IBEW) or the Utility Workers Union of America (UWUA), or one of the various trades and labor unions representing Machinist, laborers, boilermakers, millwrights, ironworkers etc.

Economics

The Bruce Nuclear Generating Station, the largest nuclear power facility in the world[13]

The economics of new nuclear power stations is a controversial subject, and multibillion-dollar investments ride on the choice of an energy source. Nuclear power stations typically have high capital costs, but low direct fuel costs, with the costs of fuel extraction, processing, use and spent fuel storage internalized costs. Therefore, comparison with other power generation methods is strongly dependent on

assumptions about construction timescales and capital financing for nuclear stations. Cost estimates take into account station decommissioning and nuclear waste storage or recycling costs in the United States due to the Price Anderson Act. With the prospect that all spent nuclear fuel/"nuclear waste" could potentially be recycled by using future reactors, generation IV reactors are being designed to completely close the nuclear fuel cycle. However, up to now, there has not been any actual bulk recycling of waste from a NPP, and on-site temporary storage is still being used at almost all plant sites due to waste repository

construction problems. Only Finland has stable repository plans, therefore from a worldwide perspective, long-term waste storage costs are uncertain.

Some nuclear reactors in operation release clouds of non-radioactive water vapor to get rid of waste heat. Pictured: Doel Nuclear Power Station

On the other hand, construction, or capital cost aside, measures to mitigate global warming such as a carbon tax or carbon emissions trading, increasingly favor the

economics of nuclear power. Further efficiencies are hoped to be achieved through more advanced reactor designs, Generation III reactors promise to be at least 17% more fuel efficient, and have lower capital costs, while futuristic Generation IV reactors promise 10000-30000% greater fuel efficiency and the elimination of nuclear waste.

In Eastern Europe, a number of long-established projects are struggling to find finance, notably Belene in Bulgaria and the additional reactors at Cernavoda in Romania, and some potential backers have pulled out.[14] Where cheap gas is

available and its future supply relatively secure, this also poses a major problem for nuclear projects.[14]

Analysis of the economics of nuclear power must take into account who bears the risks of future uncertainties. To date all operating nuclear power stations were developed by state-owned or regulated utility monopolies[15] where many of the risks associated with construction costs, operating performance, fuel price, and other factors were borne by consumers rather than suppliers. Many countries have now liberalized the electricity market where these risks and the risk of cheaper

competitors emerging before capital costs are recovered, are borne by station suppliers and operators rather than consumers, which leads to a significantly different evaluation of the economics of new nuclear power stations.[16]

Following the 2011 Fukushima I nuclear accidents, costs are likely to go up for currently operating and new nuclear power stations, due to increased requirements for on-site spent fuel management and elevated design basis threats.[17] However many designs, such as the currently under construction AP1000, use passive nuclear safety cooling systems, unlike those of

Fukushima I which required active cooling systems, which largely eliminates the need to spend more on redundant back up safety equipment.

Safety and accidents

In his book, *Normal accidents*, Charles Perrow says that multiple and unexpected failures are built into society's complex and tightly-coupled nuclear reactor systems. Such accidents are unavoidable and cannot be designed around.[18] An interdisciplinary team from MIT has estimated that given the expected growth of nuclear power from 2005 – 2055, at

least four serious nuclear accidents would be expected in that period.[19][20] However the MIT study does not take into account improvements in safety since 1970.[21][22] To date, there have been five serious accidents (core damage) in the world since 1970 (one at Three Mile Island in 1979; one at Chernobyl in 1986; and three at Fukushima-Daiichi in 2011), corresponding to the beginning of the operation of generation II reactors. This leads to on average one serious accident happening every eight years worldwide.

Modern nuclear reactor designs have had numerous safety improvements since the

first-generation nuclear reactors. Nuclear power plants cannot explode like a nuclear bomb because the fuel for uranium reactors is not enriched enough, and nuclear weapons require precision explosives to force fuel into a small enough volume to go supercritical. Most reactors require continuous temperature control to prevent a core meltdown, which has occurred on a few occasions through accident or natural disaster, releasing radiation and making the surrounding area uninhabitable. Plants must be defended against theft of nuclear material (for example to make a dirty bomb) and attack by enemy military (which has occurred)[23]

planes or missiles, or planes hijacked by terrorists.

Controversy

The abandoned city of Prypiat, Ukraine, following the Chernobyl disaster. The Chernobyl nuclear power station is in the background.

The nuclear power debate is about the controversy[24][25][26][27] which has surrounded the deployment and use of nuclear fission reactors to generate

electricity from nuclear fuel for civilian purposes. The debate about nuclear power peaked during the 1970s and 1980s, when it "reached an intensity unprecedented in the history of technology controversies", in some countries.[28][29]

Proponents argue that nuclear power is a sustainable energy source which reduces carbon emissions and can increase energy security if its use supplants a dependence on imported fuels.[30] Proponents advance the notion that nuclear power produces virtually no air pollution, in contrast to the chief viable alternative of fossil fuel. Proponents also believe that nuclear

power is the only viable course to achieve energy independence for most Western countries. They emphasize that the risks of storing waste are small and can be further reduced by using the latest technology in newer reactors, and the operational safety record in the Western world is excellent when compared to the other major kinds of power plants.[31]

Opponents say that nuclear power poses many threats to people and the environment, and that costs do not justify benefits. Threats include health risks and environmental damage from uranium mining, processing and transport, the risk

of nuclear weapons proliferation or sabotage, and the unsolved problem of radioactive nuclear waste.[32][33][34] Another environmental issue is discharge of hot water into the sea. The hot water modifies the environmental conditions for marine flora and fauna. They also contend that reactors themselves are enormously complex machines where many things can and do go wrong, and there have been many serious nuclear accidents.[35][36] Critics do not believe that these risks can be reduced through new technology.[37] They argue that when all the energy-intensive stages of the nuclear fuel chain are considered, from uranium mining to

nuclear decommissioning, nuclear power is not a low-carbon electricity source.[38][39][40] Those countries that do not contain uranium mines cannot achieve energy independence through existing nuclear power technologies. Actual construction costs often exceed estimates, and spent fuel management costs do not have a clear time limit.

Reprocessing

Nuclear reprocessing technology was developed to chemically separate and recover fissionable plutonium from irradiated nuclear fuel.[41] Reprocessing

serves multiple purposes, whose relative importance has changed over time. Originally reprocessing was used solely to extract plutonium for producing nuclear weapons. With the commercialization of nuclear power, the reprocessed plutonium was recycled back into MOX nuclear fuel for thermal reactors.[42] The reprocessed uranium, which constitutes the bulk of the spent fuel material, can in principle also be re-used as fuel, but that is only economic when uranium prices are high or disposal is expensive. Finally, the breeder reactor can employ not only the recycled plutonium and uranium in spent fuel, but all the actinides, closing the nuclear fuel

cycle and potentially multiplying the energy extracted from natural uranium by more than 60 times.[43]

Nuclear reprocessing reduces the volume of high-level waste, but by itself does not reduce radioactivity or heat generation and therefore does not eliminate the need for a geological waste repository. Reprocessing has been politically controversial because of the potential to contribute to nuclear proliferation, the potential vulnerability to nuclear terrorism, the political challenges of repository siting (a problem that applies equally to direct disposal of spent fuel), and because of its high cost compared to

the once-through fuel cycle.[44] In the United States, the Obama administration stepped back from President Bush's plans for commercial-scale reprocessing and reverted to a program focused on reprocessing-related scientific research.[45]

Accident indemnification

The Vienna Convention on Civil Liability for Nuclear Damage puts in place an international framework for nuclear liability.[46] However states with a majority of the world's nuclear power stations, including the U.S., Russia, China and

Japan, are not party to international nuclear liability conventions.

In the U.S., insurance for nuclear or radiological incidents is covered (for facilities licensed through 2025) by the Price-Anderson Nuclear Industries Indemnity Act.

Under the Energy policy of the United Kingdom through its Nuclear Installations Act 1965, liability is governed for nuclear damage for which a UK nuclear licensee is responsible. The Act requires compensation to be paid for damage up to a limit of £150 million by the liable

operator for ten years after the incident. Between ten and thirty years afterwards, the Government meets this obligation. The Government is also liable for additional limited cross-border liability (about £300 million) under international conventions (Paris Convention on Third Party Liability in the Field of Nuclear Energy and Brussels Convention supplementary to the Paris Convention).[47]

Decommissioning

Nuclear decommissioning is the dismantling of a nuclear power station and decontamination of the site to a state no

longer requiring protection from radiation for the general public. The main difference from the dismantling of other power stations is the presence of radioactive material that requires special precautions to remove and safely relocate to a waste repository.

Generally speaking, nuclear stations were originally designed for a life of about 30 years.[48][49] Newer stations are designed for a 40 to 60-year operating life.[50] The Centurion Reactor is a future class of nuclear reactor that is being designed to last 100 years.[51] One of the major limiting wear factors is the

deterioration of the reactor's pressure vessel under the action of neutron bombardment,[49] however in 2018 Rosatom announced it had developed a thermal annealing technique for reactor pressure vessels which ameliorates radiation damage and extends service life by between 15 and 30 years.[52]

Decommissioning involves many administrative and technical actions. It includes all clean-up of radioactivity and progressive demolition of the station. Once a facility is decommissioned, there should no longer be any danger of a radioactive accident or to any persons

visiting it. After a facility has been completely decommissioned it is released from regulatory control, and the licensee of the station no longer has responsibility for its nuclear safety.

Historic accidents

The 2011 Fukushima Daiichi nuclear disaster in Japan, the worst nuclear accident in 25 years, displaced 50,000 households after radiation leaked into the air, soil and sea.[53] *Radiation checks led to bans of some shipments of vegetables and fish.*[54]

The Chernobyl disaster occurred in April 1986, it is considered the worst nuclear accident in history. An experiment was being carried out on one of the reactors in the plant. The purpose of the experiment was to find out the reactor's safety in the event of the failure of the main electricity supply to the plant. Right after the experiment began there was a steam explosion which exposed the reactor's graphite moderator to air, which caused it to ignite. The resulting fire sent highly radioactive plumes of smoke into the atmosphere for about ten days. The radioactive plume spread over large areas of Europe. Approximately 350,000 people

were evacuated from the 3200 kilometers squared exclusion zone. The accident caused 31 direct deaths from the explosion and radiation poisoning, and several more deaths in the population exposed to high radiation doses.[55]

The nuclear industry says that new technology and oversight have made nuclear station much safer, but 57 small accidents have occurred since the Chernobyl disaster in 1986 until 2008. Two thirds of these mishaps occurred in the US.[19] The French Atomic Energy Agency (CEA) has concluded that technical

innovation cannot eliminate the risk of human errors in nuclear station operation.

According to Benjamin Sovacool, an interdisciplinary team from MIT in 2003 estimated that given the expected growth of nuclear power from 2005 – 2055, at least four serious nuclear accidents would be expected in that period.[19] However the MIT study does not take into account improvements in safety since 1970.[21][22]

Flexibility of nuclear power stations

Nuclear stations are used primarily for base load because of economic

considerations. The fuel cost of operations for a nuclear station is smaller than the fuel cost for operation of coal or gas plants. Since most of the cost of nuclear power plant is capital cost, there is almost no cost saving by running it at less than full capacity.

Nuclear power plants are routinely used in load following mode on a large scale in France, although "it is generally accepted that this is not an ideal economic situation for nuclear stations."[56] Unit A at the German Biblis Nuclear Power Plant is designed to in- and decrease its output 15% per minute between 40 and 100% of

its nominal power.[57] Boiling water reactors normally have load-following capability, implemented by varying the recirculation water flow.

Future power stations

A new generation of designs for nuclear power stations, known as the Generation IV reactors, are the subject of active research. Many of these new designs specifically attempt to make fission reactors cleaner, safer and/or less of a risk to the proliferation of nuclear weapons. Passively safe stations (such as the ESBWR) are available to be built[58] and

other reactors that are designed to be nearly fool-proof are being pursued.[59] Fusion reactors, which are still in the early stages of development, diminish or eliminate some of the risks associated with nuclear fission.[60]

Two 1600 MWe European Pressurized Reactors (EPRs) are being built in Europe, and two are being built in China. The reactors are a joint effort of French AREVA and German Siemens AG, and will be the largest reactors in the world. One EPR is in Olkiluoto, Finland, as part of the Olkiluoto Nuclear Power Plant. The reactor was originally scheduled to go online in 2009,

but has been repeatedly delayed,[61][62] and as of September 2014 has been pushed back to 2018.[63] Preparatory work for the EPR at the Flamanville Nuclear Power Plant in Flamanville, Manche, France was started in 2006, with a scheduled completion date of 2012.[64] The French reactor has also been delayed, and was projected, in 2013, to launch in 2016.[65][66] The two Chinese EPRs are part of the Taishan Nuclear Power Plant in Taishan, Guangdong. The Taishan reactors were scheduled to go online in 2014 and 2015,[67] but that has been delayed to 2017.[68]

As of March 2007, there are seven nuclear power stations under construction in India, and five in China.[69]

In November 2011 Gulf Power stated that by the end of 2012 it hopes to finish buying off 4000 acres of land north of Pensacola, Florida in order to build a possible nuclear power station.[70]

In 2010 Russia launched a floating nuclear power station. The £100 million vessel, the Akademik Lomonosov, is the first of seven stations that will bring vital energy resources to remote Russian regions.[71]

By 2025, Southeast Asia nations plan to have a total of 29 nuclear power stations: Indonesia will have 4 nuclear power stations, Malaysia 4, Thailand 5 and Vietnam 16 from nothing at all in 2011.[72]

In 2013 China had 32[73] nuclear reactors under construction, the highest number in the world.

Expansion at two nuclear power stations in the United States, Vogtle and V. C. Summer Nuclear Power Station, located in Georgia and South Carolina, respectively, were scheduled to be completed between 2016 and 2019. The construction of the

two South Carolina reactors have been abandoned due to cost overruns and the bankruptcy of Westinghouse Electric Company (who designed and was building the reactors) in March 2017[74]. The two new Vogtle reactors, and the two new reactors at Virgil C. Summer Nuclear Station, represented the first nuclear power construction projects in the United States since the Three Mile Island nuclear accident in 1979.

The UK government has given the go-ahead for the Hinkley Point C nuclear power station.[75]

Several countries have begun thorium-based nuclear power programs. Thorium is four times more abundant in the earth's crust than uranium. Over 60% of thorium's ore monazite is found in five countries: Australia, the United States, India, Brazil, and Norway. These thorium resources are enough to power current energy needs for thousands of years.[76] The thorium fuel cycle is able to generate nuclear energy with a lower output of radiotoxic waste than the uranium fuel cycle.[77]

See also

- List of nuclear reactors

- List of nuclear power stations (> 1,000 MW net capacity)
- Auxiliary feedwater
- Gerald W. Brown, American whistleblower on passive fire protection/circuit integrity deficiencies in US and Canadian plants
- Containment building
- Fossil-fuel power station
- Nuclear fuel cycle
- Nuclear Information and Resource Service
- Nuclear power by country

- Nuclear Regulatory Commission of the USA
- Safety engineering
- SCRAM
- U.S. Federal Emergency Management Agency (FEMA)
- Uranium market

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